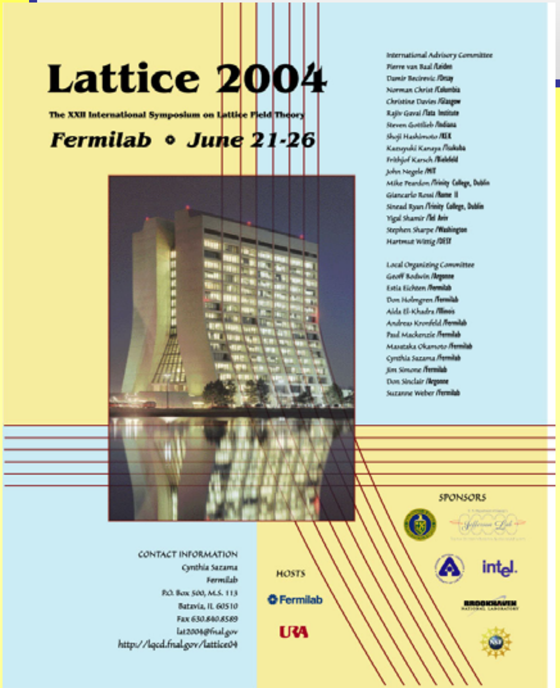
THE ROLE OF LATTICE QCD IN FLAVOR PHYSICS



Vittorio Lubicz

DIPARTIMENTO DI FISICA EDOARDO AMALDI

UNIVERSITÀ DEGLI STUDI ROMA TRE

OUTLINE

1. Flavor physics and its motivations
2. First row unitarity and the Cabibbo angle
3. The unitarity triangle analysis
4. New Physics

see also talks by:
M.Wingate (LQCD)
I.Shipsey (Exp.)

Special thanks to P.Gambino, L.Giusti, G.Isidori, S.Sharpe, and all the members of the UTfit Collaboration

1

FLAVOR PHYSICS

AND ITS

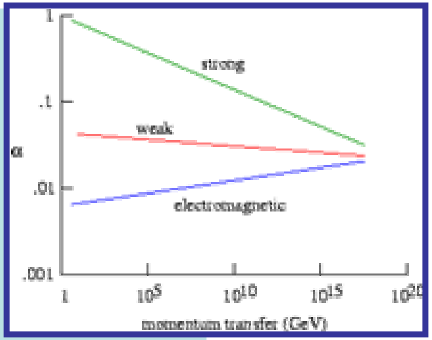
MOTIVATIONS

THE STANDARD MODEL:
A LOW ENERGY EFFECTIVE THEORY

CONCEPTUAL PROBLEMS   **The most obvious:**

- Gravity: $M_{Planck} = (\hbar c/G_N)^{1/2} \approx 10^{19}$ GeV

PHENOMENOLOGICAL INDICATIONS



- Unification of couplings ($M_{GUT} \approx 10^{15}$-10^{16} GeV)
- Dark matter ($\Omega_M \approx 0.35$)
- Neutrino masses
- Matter/Anti-matter asymmetry (not enough ~~CP~~ in the SM)
- Cosmological vacuum energy

THE "NATURAL" CUT-OFF:

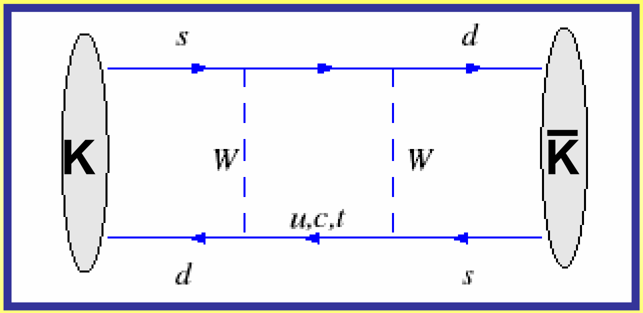
NEW PHYSICS MUST BE VERY "SPECIAL"

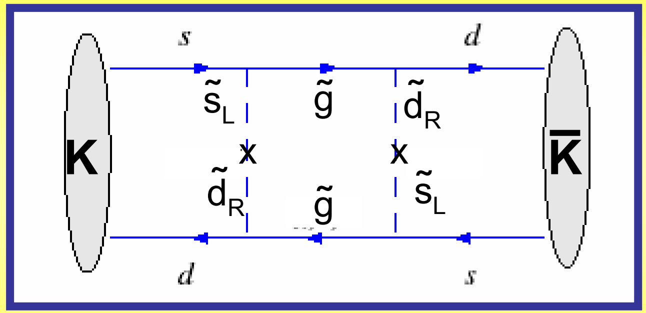
$$\delta m_H^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 \Lambda^2 \approx (0.3\ \Lambda)^2 \longrightarrow \Lambda = O(1\ \text{TeV})$$

MOTIVATIONS FOR FLAVOR PHYSICS

- We do not understand flavor physics:
  Why 3 families? Why the hierarchy of masses?

- We expect New Physics effects in the flavor sector:





THE FLAVOR PROBLEM: $\Lambda_{K^0-\bar{K}^0} \approx O(100\ \text{TeV})$

- 10 parameters in the quark sector (6 m_q + 4 CKM)

- Is the CKM mechanism and its explanation of ~~CP~~ correct?

PRECISION ERA OF FLAVOR PHYSICS

$\varepsilon_K = (2.271 \pm 0.017) \times 10^{-3}$ 0.7%

$\Delta m_d = (0.503 \pm 0.006)\ \mathrm{ps}^{-1}$ 1%

$\sin(2\beta) = 0.734 \pm 0.054$ 7%

....

EXPERIMENTS

We need to control the theoretical input parameters at a comparable level of accuracy !!

2

FIRST ROW UNITARITY AND THE CABIBBO ANGLE

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

The most stringent unitarity test

SFT:	$|V_{ud}| = 0.9740 \pm 0.0005$	Extremely precise, 9 expts
N β-dec:	$|V_{ud}| = 0.9731 \pm 0.0015$	g_V/g_A, will be improved at PERKEO, Heidelb.
π_{e3}**:**	$|V_{ud}| = 0.9765 \pm 0.0056$	Theor. clean, but BR=10^{-8} PIBETA at PSI
Average:	$|V_{ud}| = 0.9739 \pm 0.0005$	G.Isidori et al., CKM 2002 Workshop

K→πeν:	$|V_{us}| = 0.2196 \pm 0.0026$	PDG 2002 average

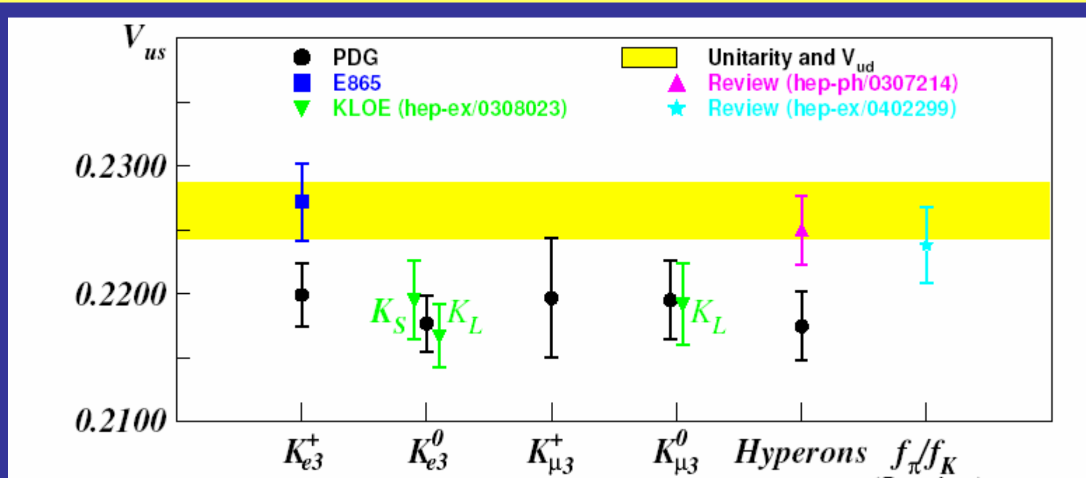
b→u	$|V_{ub}| = 0.0036 \pm 0.0007$	$|V_{ub}|^2 \approx 10^{-5}$

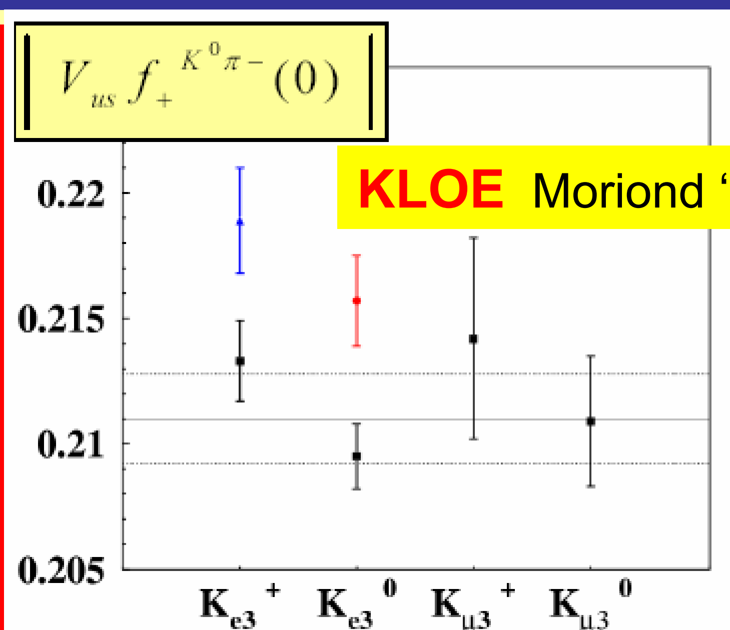
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0042 \pm 0.0019$$

"Old" 2σ discrepancy

The NEW experimental results

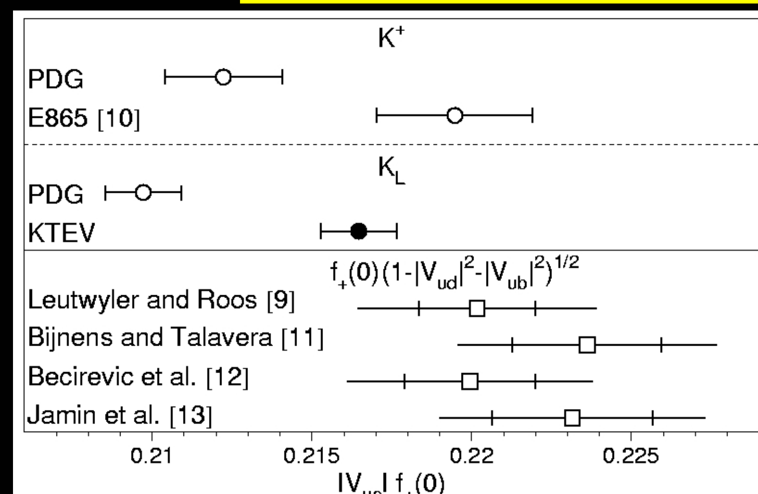
BNL-E865
PRL 91, 261802
(and Moriond '04)





KLOE Moriond '04

KTeV hep-ex/0406001



Theory: 2 recent lattice contributions

1) LEPTONIC DECAYS:

$$\frac{\Gamma(K \to \mu \bar{\nu}_\mu(\gamma))}{\Gamma(\pi \to \mu \bar{\nu}_\mu(\gamma))} = \frac{|V_{us}|^2 f_K^2 m_K \left(1 - \frac{m_\mu^2}{m_K^2}\right)^2}{|V_{ud}|^2 f_\pi^2 m_\pi \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2} \, 0.9930(35)$$

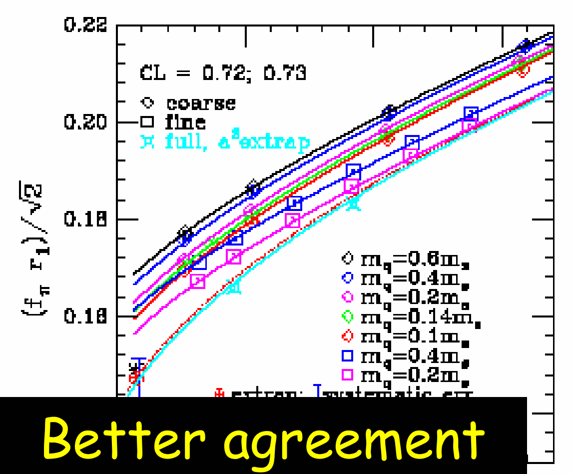
[Rad.Corr.]

Precise f_K/f_π, MILC Latt.'03-04 Asqtad action, $N_f=3$

$f_\pi = 129.5 \pm 0.9_{stat} \pm 3.6_{syst}$ MeV

$f_K = 156.6 \pm 1.0_{stat} \pm 3.8_{syst}$ MeV

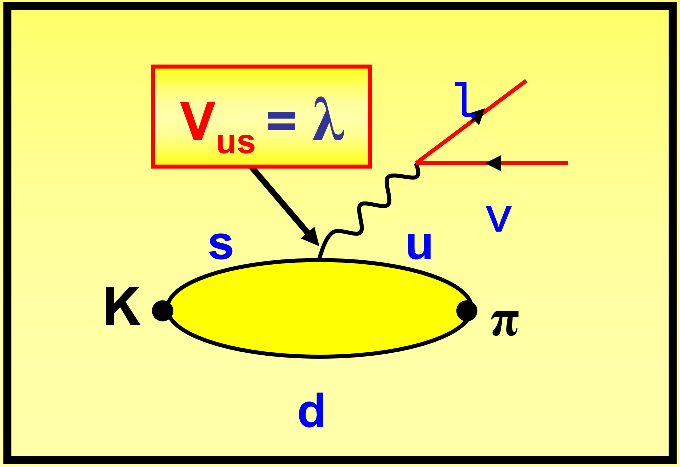
$f_K/f_\pi = 1.210 \pm 0.004_{stat} \pm 0.013_{syst}$



Better agreement with unitarity!!

C.Bernard, update of Marciano 2004: $|V_{us}| = 0.2219(26)$

2) SEMILEPTONIC Kl3 DECAYS:
Precise (quenched) calculation of f(0), SPQcdR 2004



$$\Gamma_{K\ell 3} = C^{\ell} \frac{G_F^2 |V_{us}|^2 M_K^5}{192\,\pi^3} S_{EW} (1+\delta_K^{\ell})\, I_K^{\ell}\, f_+(0)^2$$

The largest th. uncertainty from:

$$f_+(0) = 1 - O(m_s - m_u)^2$$

[Ademollo-Gatto theorem]

ChPT

$$f_+(0) = 1 + f_2 + f_4 + O(p^8)$$

Vector Current Conservation

$f_2 = -\,0.023$
Independent of L_i
(Ademollo-Gatto)

THE LARGEST UNCERTAINTY

"Standard" estimate:

Leutwyler, Roos (1984)
(QUARK MODEL)

$f_4 = -0.016 \pm 0.008$

ChPT: The complete $O(p^6)$ calculation

Post, Schilcher (2001), Bijnens, Talavera (2003)

$$f_4 = \Delta_{loops}(\mu) - \frac{8}{F_\pi^4}\left[C_{12}(\mu) + C_{34}(\mu)\right](M_K^2 - M_\pi^2)^2$$

$C_{12}(\mu)$ and $C_{34}(\mu)$ can be determined from the slope and the curvature of the scalar form factor. Experimental data, however, are not accurate enough.

... and models

Jamin et al., $f_4^{LOC} = -0.018 \pm 0.009$ [Coupled channel dispersive analysis]

Cirigliano et al., $f_4^{LOC} = -0.012$ [Resonance saturation]

Cirigliano et al., $f_4^{LOC} = -0.016 \pm 0.008$ [QM, Leutwyler and Roos]

μ = ??? $\Delta_{loops}(1\text{GeV}) = 0.004$ $\Delta_{loops}(M_\rho) = 0.015$ $\Delta_{loops}(M_\eta) = 0.031$

Cirigliano et al., $f_+^{K^0\pi^-}(0) = 0.981 \pm 0.010$

The Lattice QCD calculation

Talk by F.Mescia (and hep-ph/0403217)

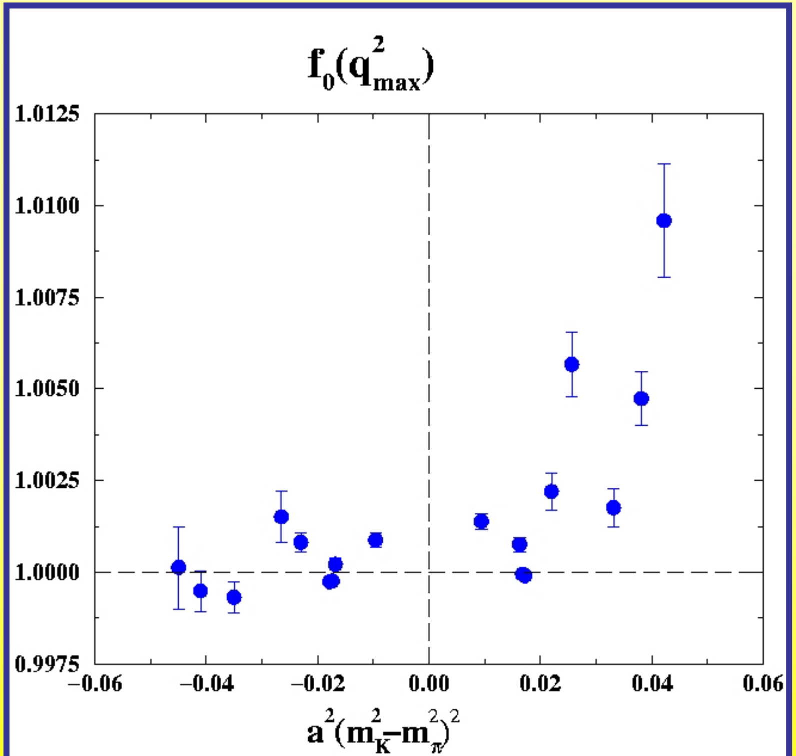
1) Evaluation of $f_0(q^2_{MAX})$

The basic ingredient is a double ratio of correlation functions:

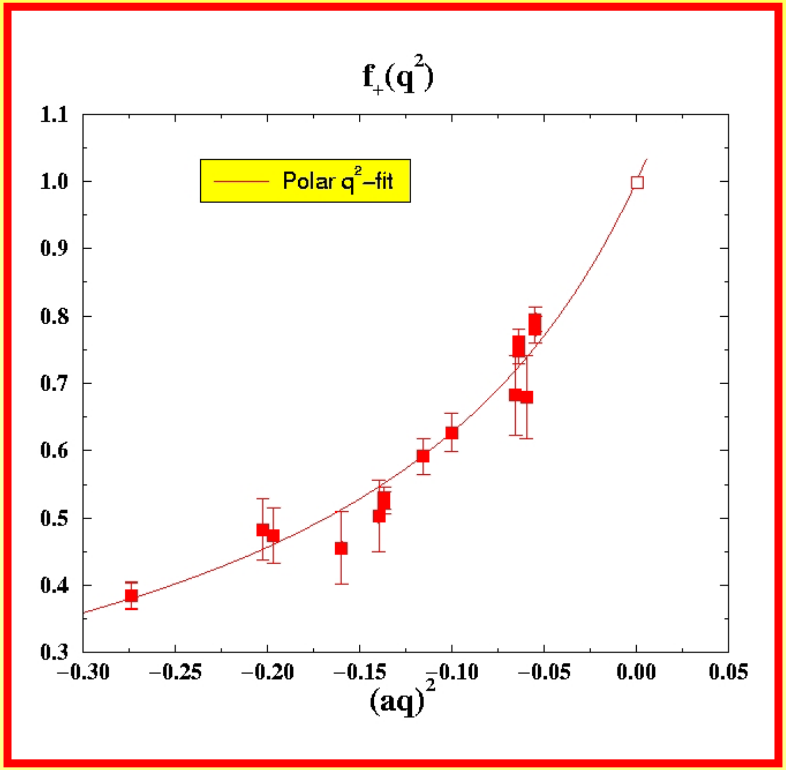
$$R = \frac{\langle \pi | \bar{s}\gamma_0 u | K \rangle \langle K | \bar{u}\gamma_0 s | \pi \rangle}{\langle \pi | \bar{u}\gamma_0 u | \pi \rangle \langle K | \bar{s}\gamma_0 s | K \rangle}$$

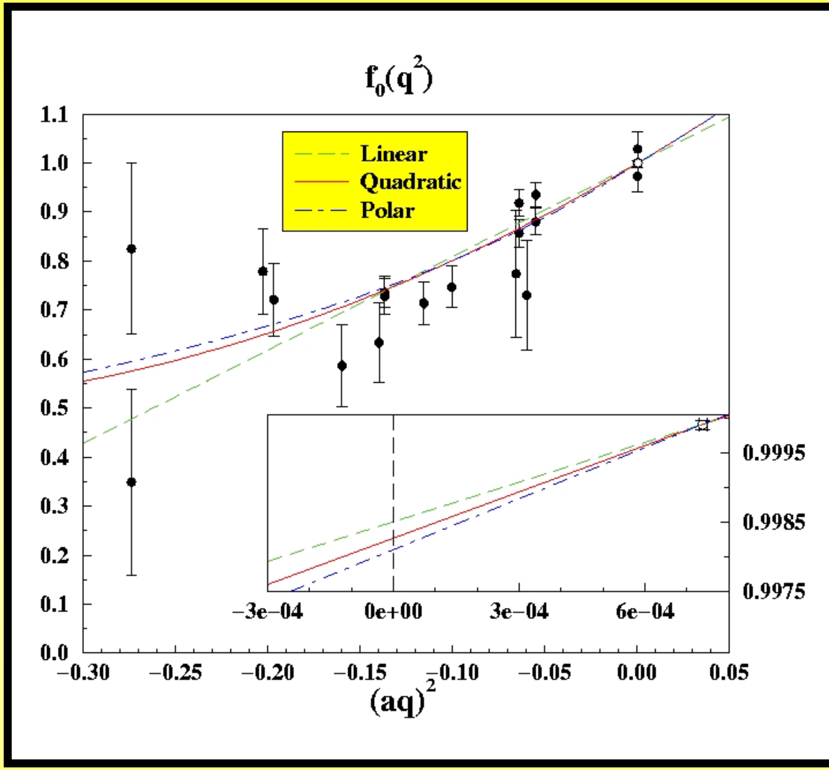
$$= \frac{(M_K + M_\pi)^2}{4 M_K M_\pi} f_0(q^2_{max})^2$$

[FNAL for B->D*]



2) Extrapolation of $f_0(q^2_{MAX})$ to $f_0(0)$



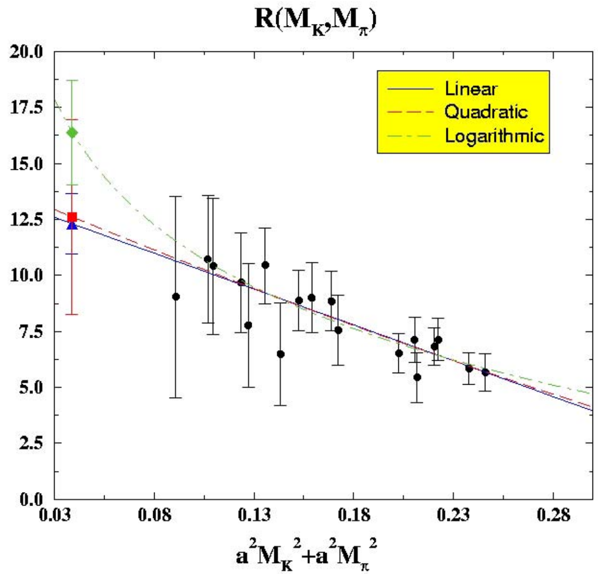


Comparison of polar fits:

LQCD: $\lambda_+ = (25 \pm 2)\,10^{-3}$ $\lambda_0 = (12 \pm 2)\,10^{-3}$

KTeV: $\lambda_+ = (24.11 \pm 0.36)\,10^{-3}$ $\lambda_0 = (13.62 \pm 0.73)\,10^{-3}$

3) Chiral extrapolation



$$R = \frac{f_+(0) - 1 - f_2^{QUEN}}{(M_K^2 - M_\pi^2)^2}$$

Computed in Quenched-ChPT

The dominant contributions to the systematic error come from the uncertainties on the q^2 and mass dependencies of the form factor

$$f_+^{K^0\pi^-}(0) = 0.960 \pm 0.005_{stat} \pm 0.007_{syst}$$

[Quenching error is not included]

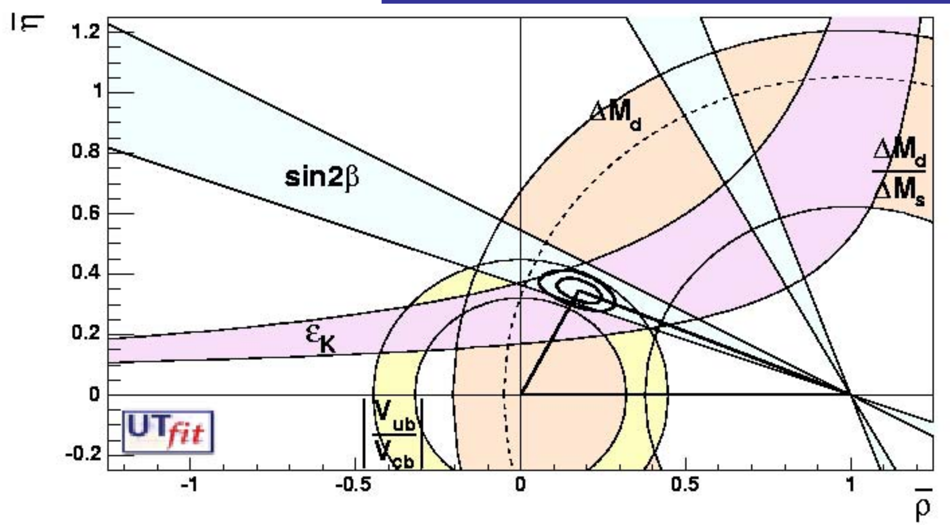
In agreement with LR!!

3

THE UNITARITY TRIANGLE ANALYSIS

THE UNITARITY TRIANGLE ANALYSIS

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

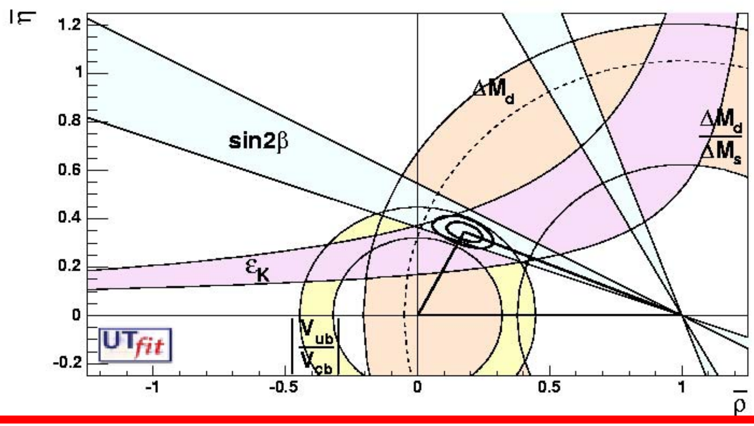


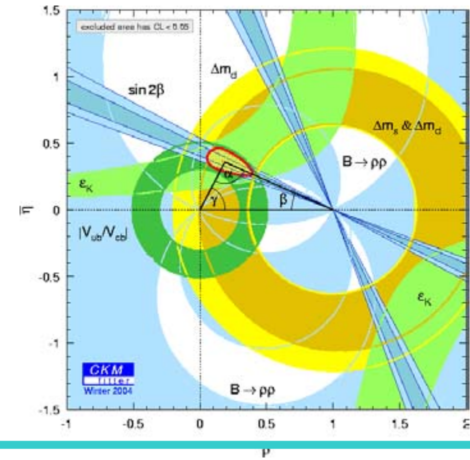
5 CONSTRAINTS
2 PARAMETERS

Hadronic Matrix Elements from LATTICE QCD

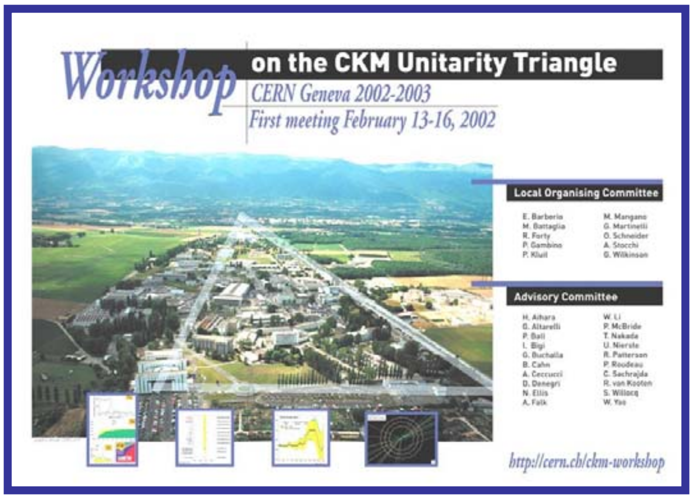
$(b \to u)/(b \to c)$	$\bar{\rho}^2 + \bar{\eta}^2$	$f_+, F(1), \ldots$
ε_K	$\bar{\eta}\,[(1-\bar{\rho}) + P]$	B_K
Δm_d	$(1-\bar{\rho})^2 + \bar{\eta}^2$	$f_{B_d}^2 B_{B_d}$
$\Delta m_d / \Delta m_s$	$(1-\bar{\rho})^2 + \bar{\eta}^2$	ξ
$A(J/\psi\, K_S)$	$\sin 2\beta(\bar{\rho}, \bar{\eta})$	—

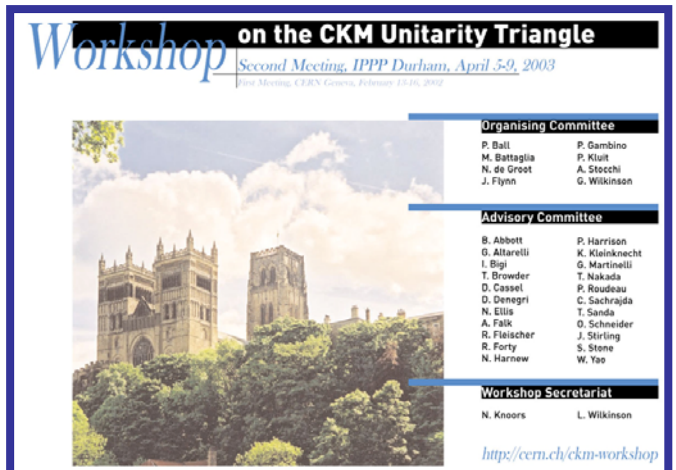
Bayesian and frequentist: 2 stat. approaches





and 2 dedicated workshop





The Bayesian approach

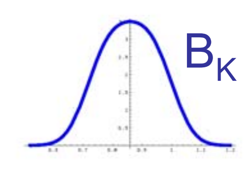
The Bayes Theorem: $P(A/B) \sim P(B/A)\, P(A)$

$$f(\bar\rho,\bar\eta,\mathbf{x}|c_1,\ldots,c_m) \sim \prod_{j=1,m} f_j(\mathbf{c}|\bar\rho,\bar\eta,\mathbf{x}) \prod_{i=1,N} f_i(x_i)\, f_o(\bar\rho,\bar\eta)$$

Integrat. over x

$$\longrightarrow \quad f(\bar\rho,\bar\eta|\mathbf{c}) \sim \mathcal{L}(\mathbf{c}|\bar\rho,\bar\eta)\, f_o(\bar\rho,\bar\eta)$$

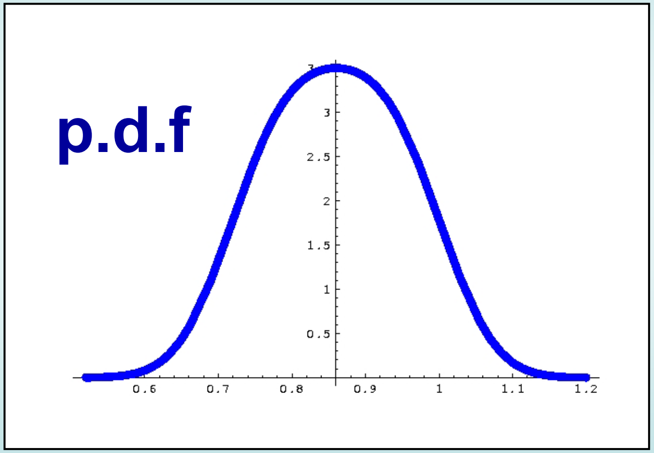
The p.d.f. $f(x_i)$ represents our "degree of beliefs"

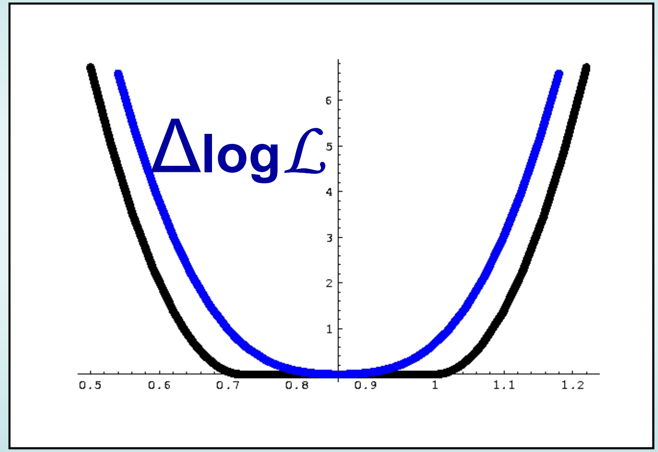


The Frequentistic approach

The theoretical likelihood do not contribute to the χ^2 of the fit while the corresponding parameters take values within the "allowed" ranges. Instances where even only one of the parameters trespasses its range are not considered.

Example: $\hat{B}_K = 0.86 \pm 0.06 \pm 0.14$





Bayesian **Frequentistic**

In the frequentistic approach the selected region does not have a precise statistical meaning ("at least 95%"). Nevertheless, if same likelihood are used, the output results are very similar

Estimates of the uncertainties for lattice determinations should be given by the lattice community

Unitary Triangle Analysis:

LQCD INPUT PARAMETERS

$K - \bar{K}$ mixing and B_K

	Stat., Match.	Quench., Chiral
$\hat{B}_K = 0.86 \pm 0.06 \pm 0.14$		
Error:	7%	16%
Projected:	7%	

$\hat{B}_K = 0.87 \pm 0.06 \pm 0.13$

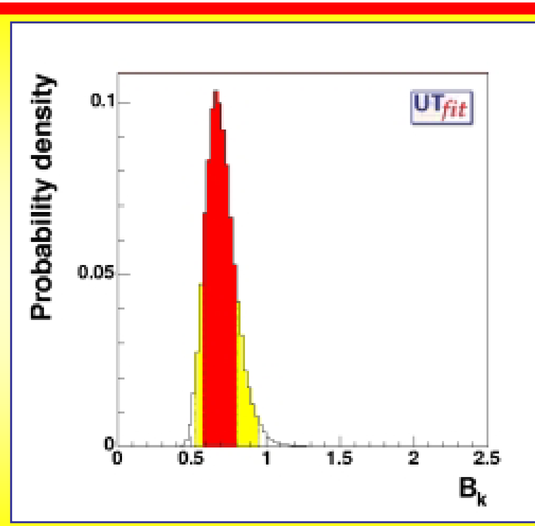
LATT03 average: D. Becirevic

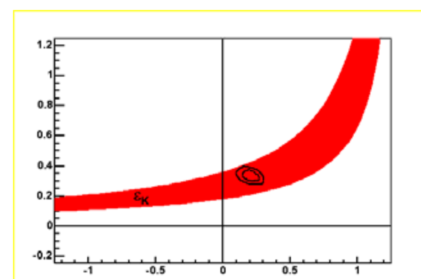
Error from other sources $\approx$ 10% (mainly V_{cb})

From the UT fit

$\hat{B}_K = 0.65 \pm 0.10$

15%





$B_{B_{d/s}} - \bar{B}_{B_{d/s}}$ mixing: $f_{B_s}\sqrt{B_{B_s}}$ and ξ (I)

Stat & Syst

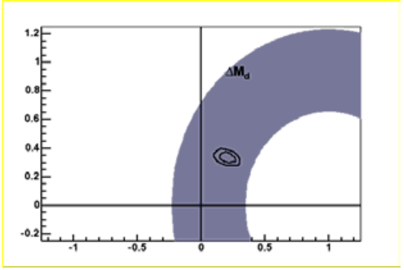
$f_{Bs}\sqrt{B_{Bs}} = 276 \pm 38$ MeV

Error: 14%

Projected: 5%

$f_{Bs}\sqrt{B_{Bs}} = 270 \pm 40$ MeV

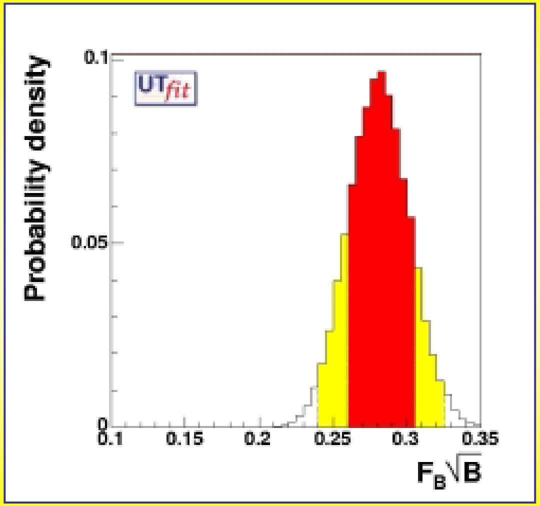
LATT03 average: A. Kronfeld



From the UT fit

$f_{Bs}\sqrt{B_{Bs}} = 279 \pm 21$ MeV

8%



$B_{B_{d/s}} - \bar{B}_{B_{d/s}}$ mixing: $f_{B_s}\sqrt{B_{B_s}}$ and ξ (II)

	Stat.	Syst.
$\xi = 1.24 \pm 0.04 \pm 0.06$		
Error:	3%	5%
Projected:	3%	

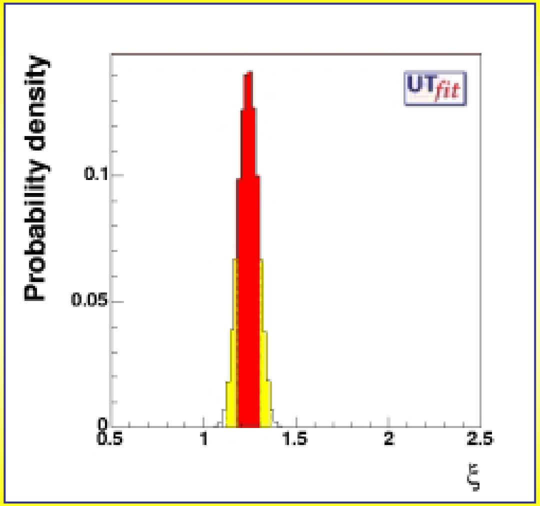
$\xi = 1.25 \pm 0.10$

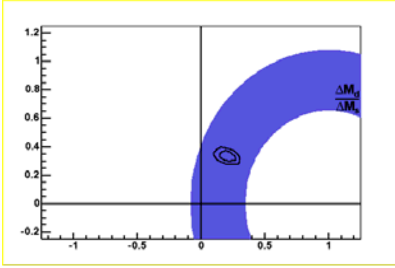
LATT03 average: A. Kronfeld

From the UT fit

$\xi = 1.22 \pm 0.05$

4%





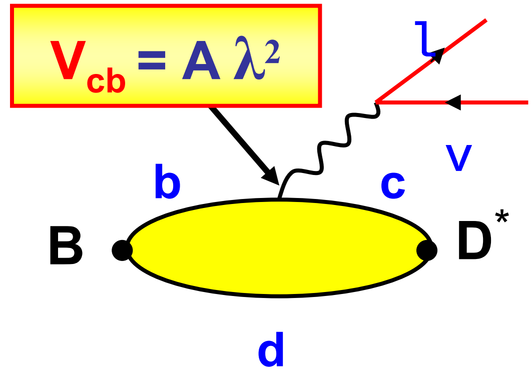
V_{cb} from exclusive semil. B-decays

	Exp.	Theor.

$$V_{cb}^{Excl.} = (42.1 \pm 1.1 \pm 1.9) \cdot 10^{-3}$$

Error: 2.6% 4.5%

Projected: ??



$$F_{B \to D^*}(1) = 0.91 \pm 0.04$$

Mainly from LQCD, FNAL
Compatible with QCDSR and HQET
+ Quark Model

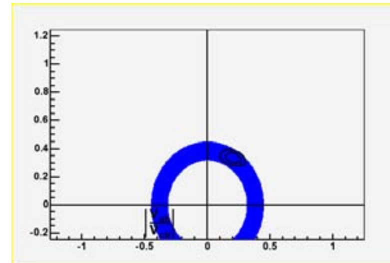
$$V_{cb}^{Incl.} = (41.4 \pm 0.7 \pm 0.6) \cdot 10^{-3}$$

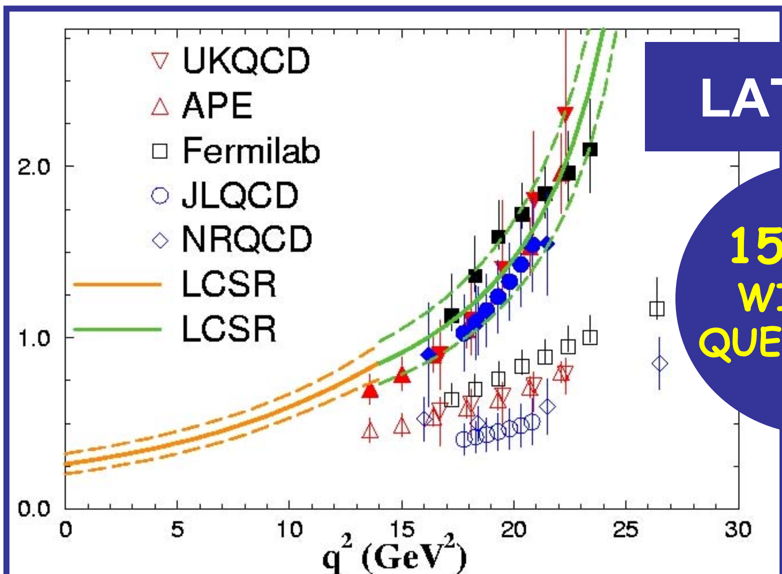
Dominant contribution to the average

$$V_{cb}^{Aver.} = (41.5 \pm 0.7) \cdot 10^{-3}$$

V_{ub} from exclusive semil. B-decays

	Exp.	Theor.
$V_{ub}^{Excl.} = (32.4$	$\pm\ 2.4$	$\pm\ 4.6) \cdot 10^{-4}$
Error:	7%	14%
Projected:	7%	

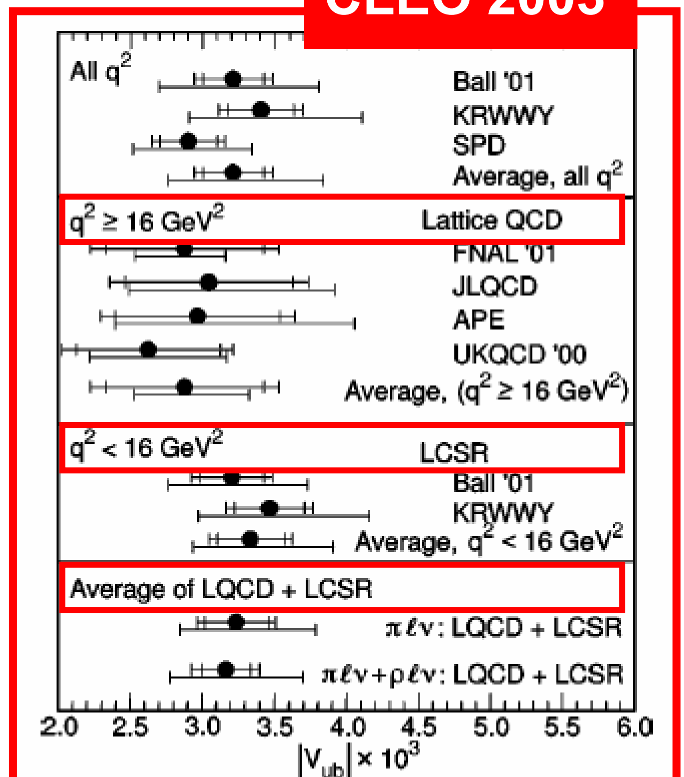




LATTICE

15-20% WITHIN QUENCHING

CLEO 2003

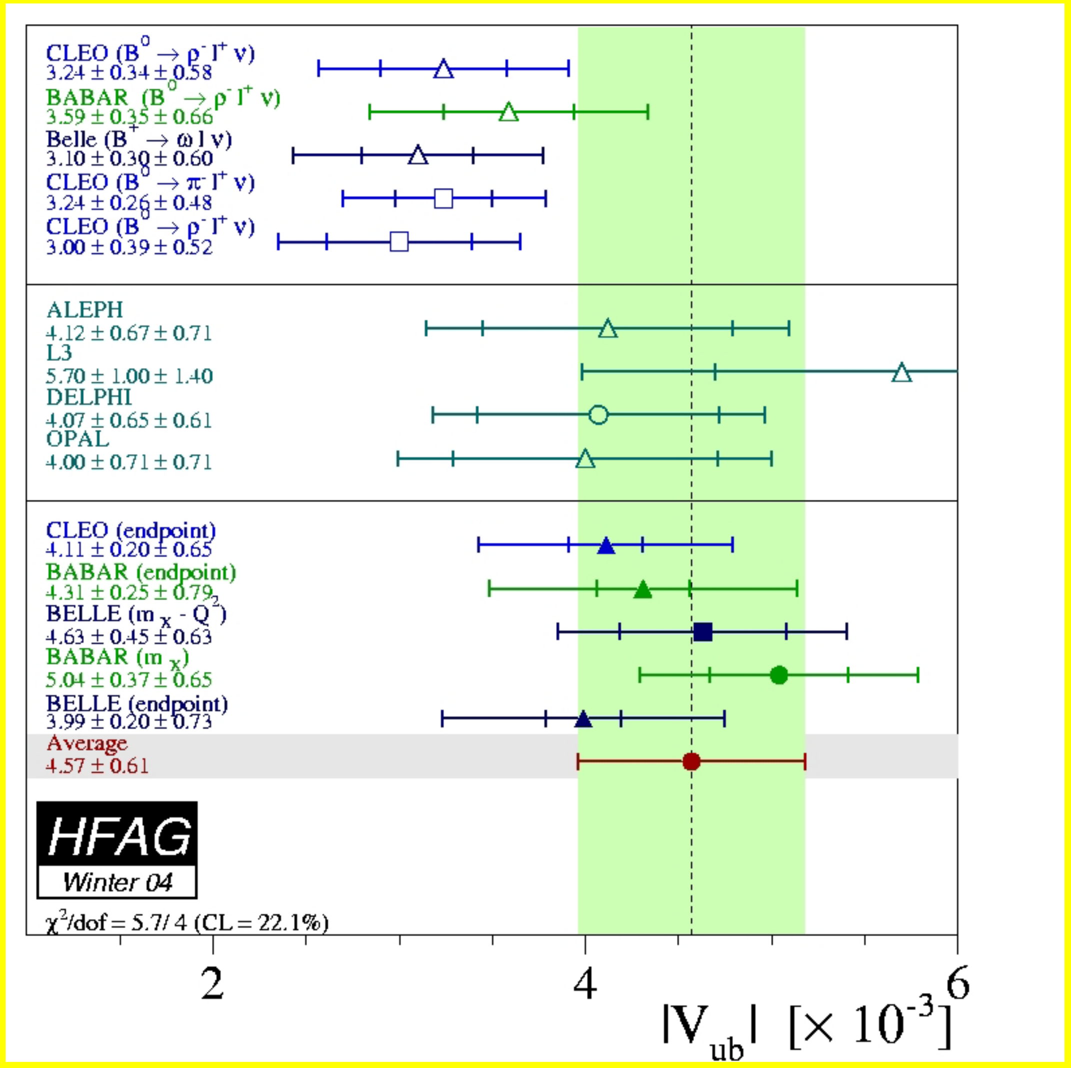


Exclusive/Inclusive V_{ub}

Exclusive

Inclusive

?



Unitary Triangle Analysis:

RESULTS AND PERSPECTIVES

UTfit Collaboration

M.Bona, M.Ciuchini, E.Franco, V.L., G.Martinelli,

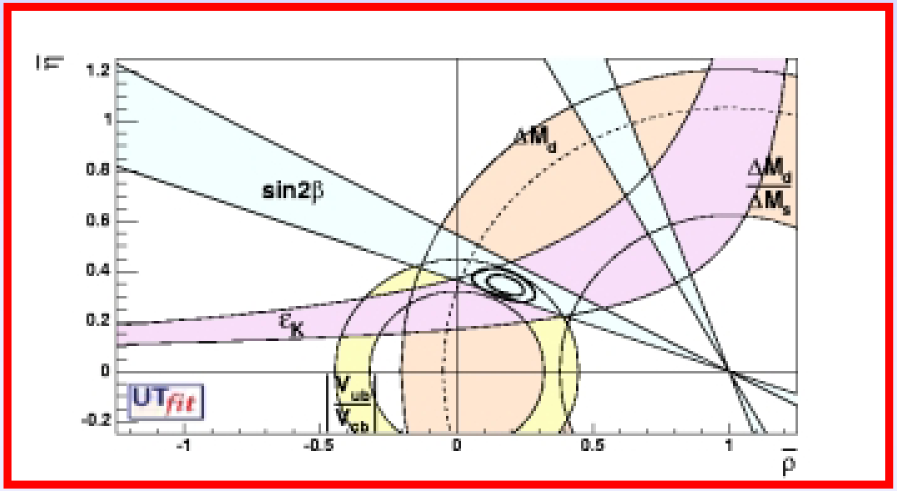
F.Parodi, M.Pierini, P.Roudeau, C.Schiavi,

L.Silvestrini, A.Stocchi

Roma, Genova, Torino, Orsay

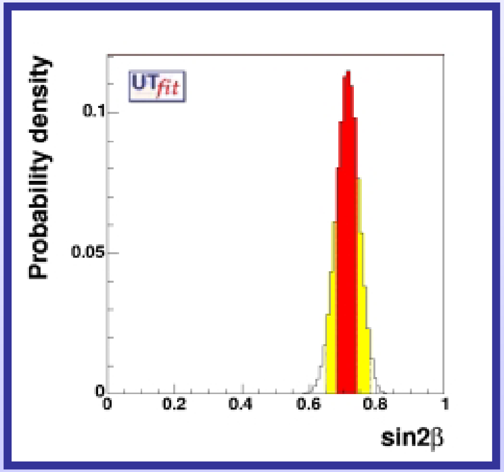
www.utfit.org

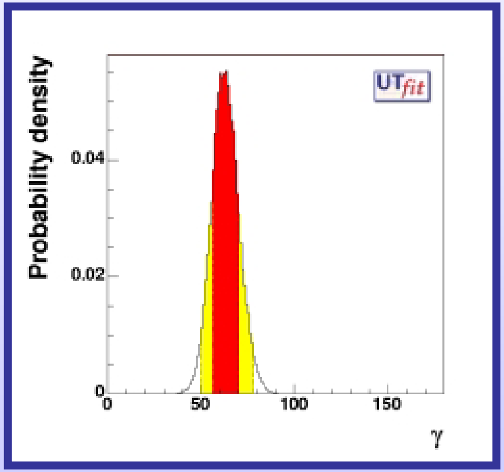
FIT RESULTS



$\bar{\rho} = 0.174 \pm 0.048$

$\bar{\eta} = 0.344 \pm 0.027$





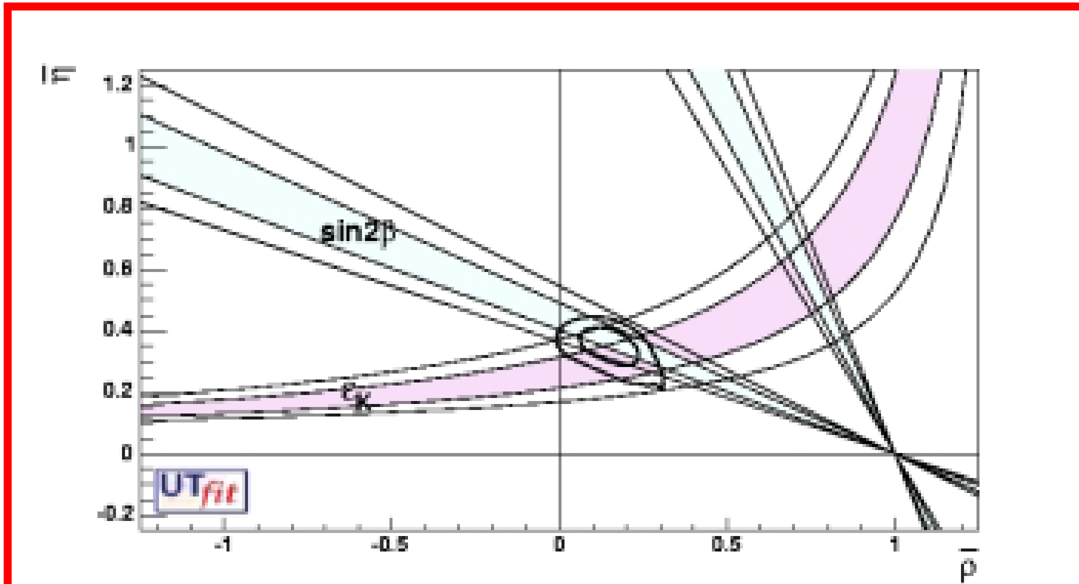
$\mathrm{Sin}2\alpha = -\,0.14 \pm 0.25$

$\mathrm{Sin}2\beta = 0.697 \pm 0.036$

$\gamma = (61.9 \pm 7.9)^{\circ}$

INDIRECT EVIDENCE OF CP VIOLATION

3 FAMILIES ⟶ - Only 1 phase - Angles from Sides



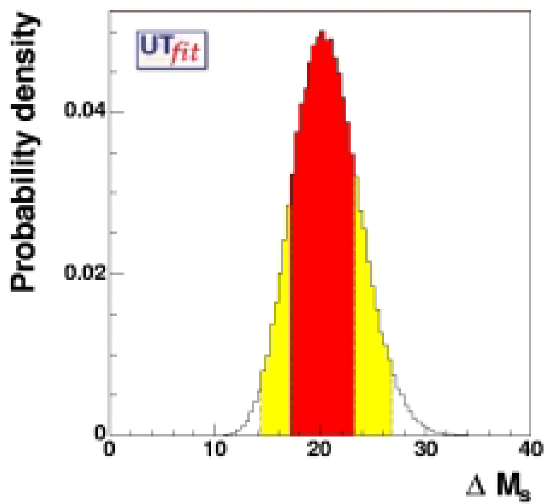
$Sin2\beta_{UT\ Sides} = 0.685 \pm 0.047$

$Sin2\beta_{J/\psi\ Ks} = 0.739 \pm 0.048$

Prediction (Ciuchini et al., 2000): **$Sin2\beta_{UTA} = 0.698 \pm 0.066$**

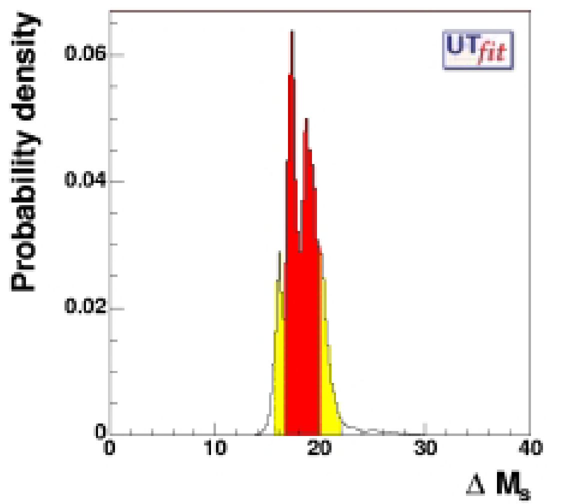
Prediction for Δm_s

Δm_s NOT USED



$\Delta m_s = (20.5 \pm 3.2)\ ps^{-1}$

WITH ALL CONSTRAINTS



$\Delta m_s = (18.0 \pm 1.6)\ ps^{-1}$

A measurement is expected at FERMILAB

IMPACT OF IMPROVED DETERMINATIONS

$B_K = 0.86 \pm 0.06 \pm \cancel{0.14}$

$\xi = 1.24 \pm 0.04 \pm \cancel{0.06}$

$V_{ub} = (32.4 \pm 2.4 \pm \cancel{4.6})\,10^{-4}$ (exclusive only)

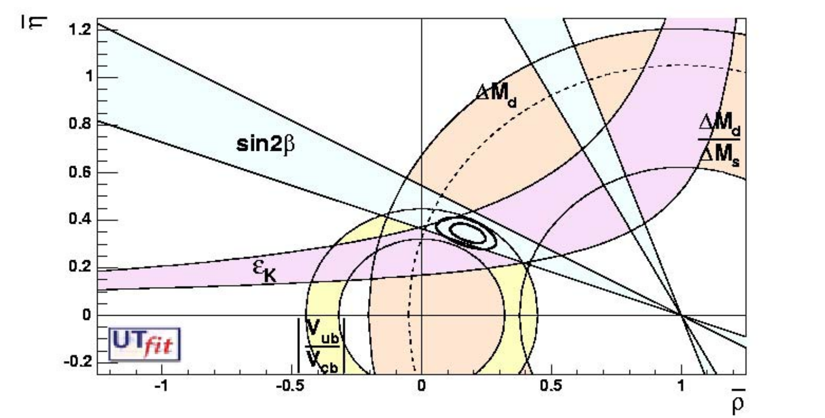
14

$f_{B_s}\sqrt{B_{B_s}} = 276 \pm 38$ MeV

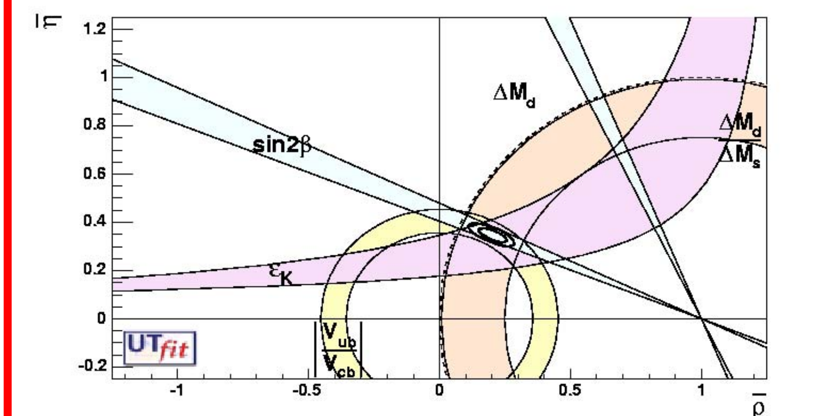
21

$\sin 2\beta = 0.734 \pm 0.054$

TODAY

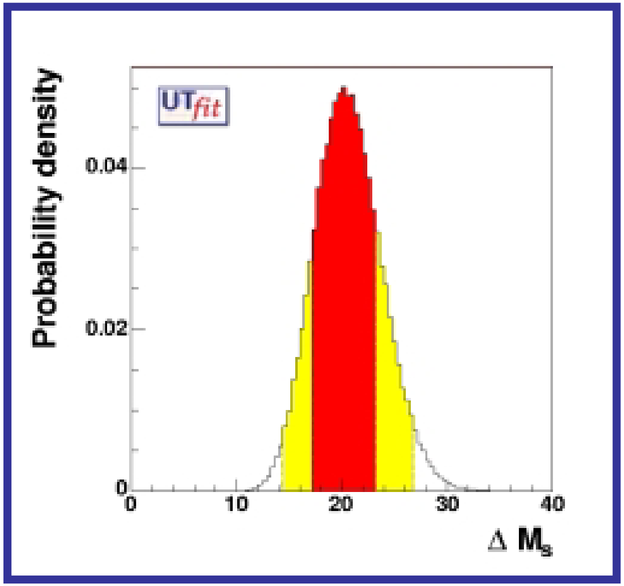


NEXT YEARS

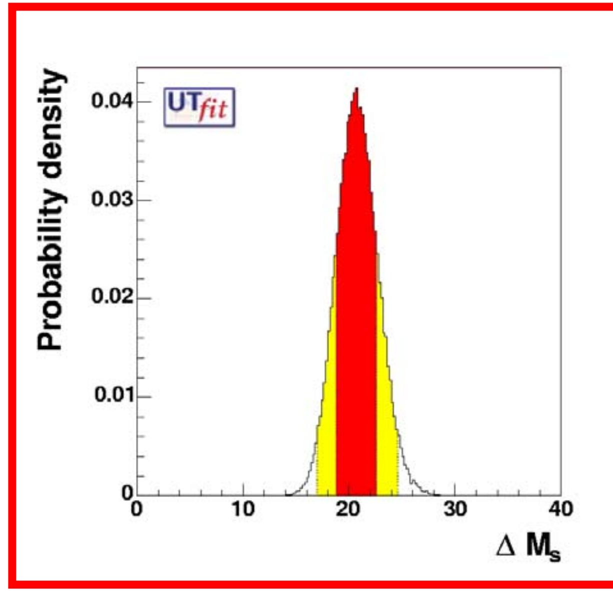


$\Delta\bar{\rho}$ = 28% → 17% (-40%) $\Delta\bar{\eta}$ = 7.8% → 5.2% (-33%)

TODAY

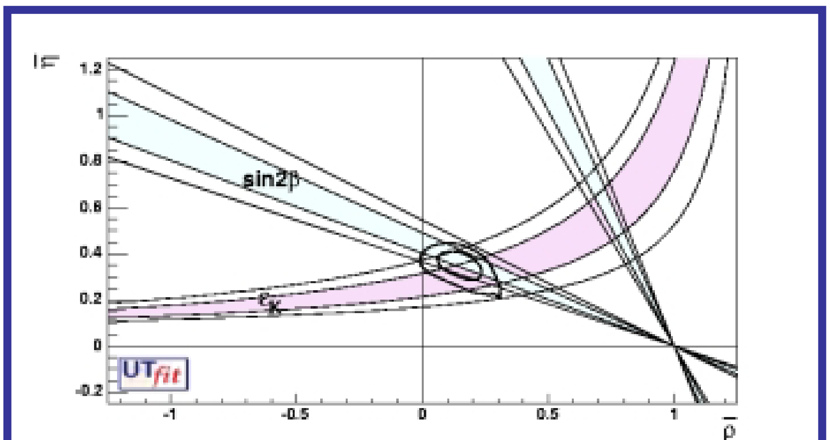


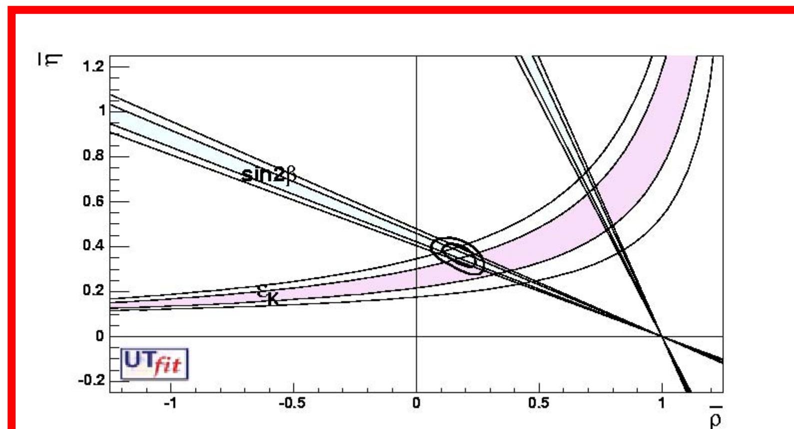
NEXT YEARS



$\Delta m_s = (20.5 \pm 3.2)\ ps^{-1}$

$\Delta m_s = (20.7 \pm 1.9)\ ps^{-1}$



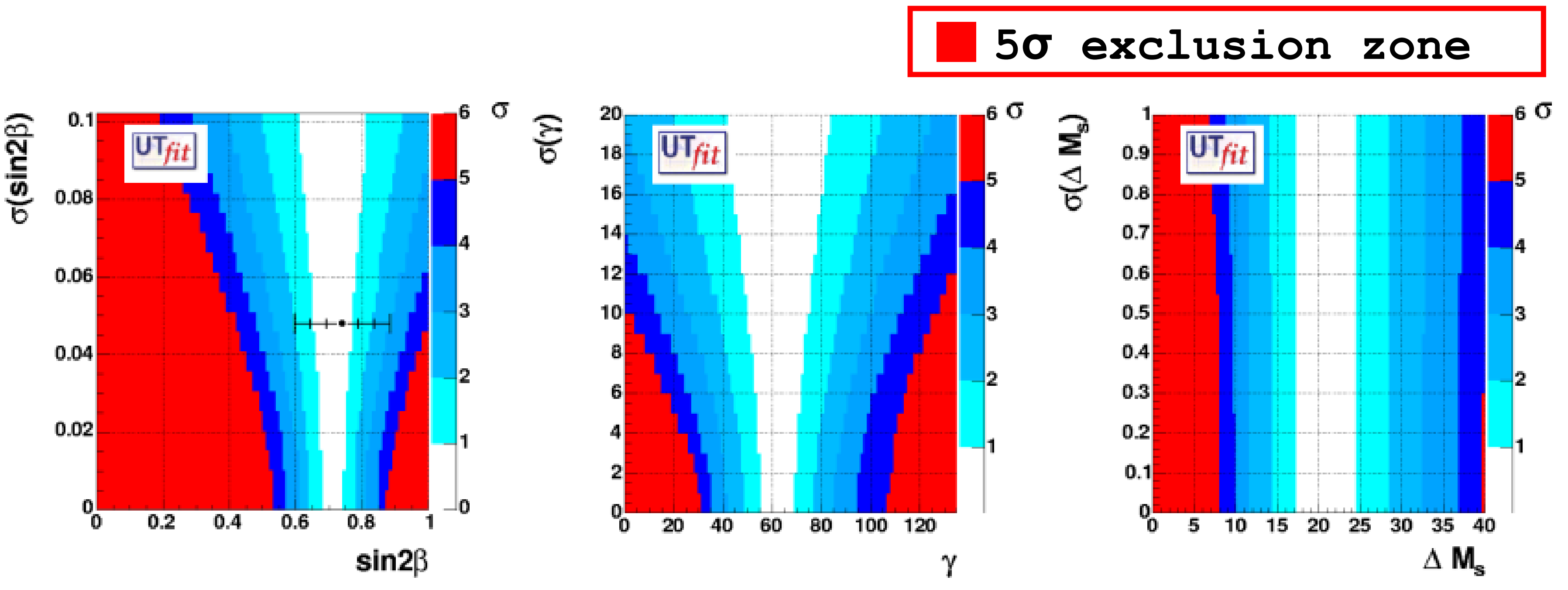


4

NEW PHYSICS

THE "COMPATIBILITY" PLOTS

1) "To which extent improved experimental determinations will be able to detect New Physics?"



Compatibility between direct and indirect determinations as a function of the measured value and its experimental uncertainty

SEARCH FOR NEW PHYSICS

2) "Given the present theoretical and experimental constraints, to which extent the UTA can still be affected by New Physics contributions?"

An interesting case:

New Physics in B_d–$\overline{B}_d$ mixing

The New Physics mixing amplitudes can be parameterized in a simple general form:

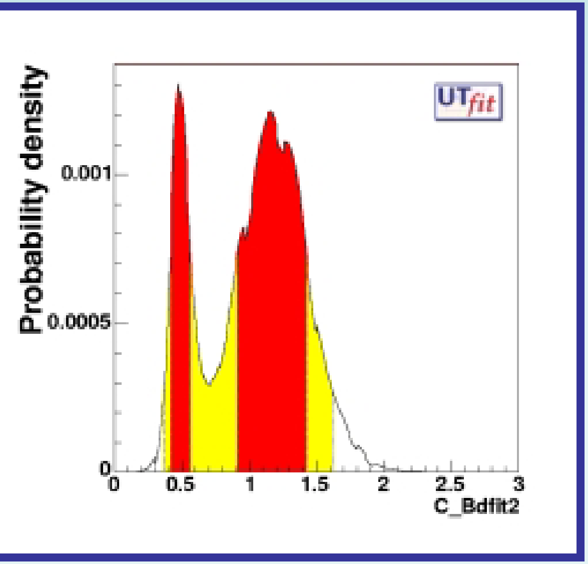
$$M_d = C_d \, e^{2i\varphi_d} (M_d)^{SM}$$

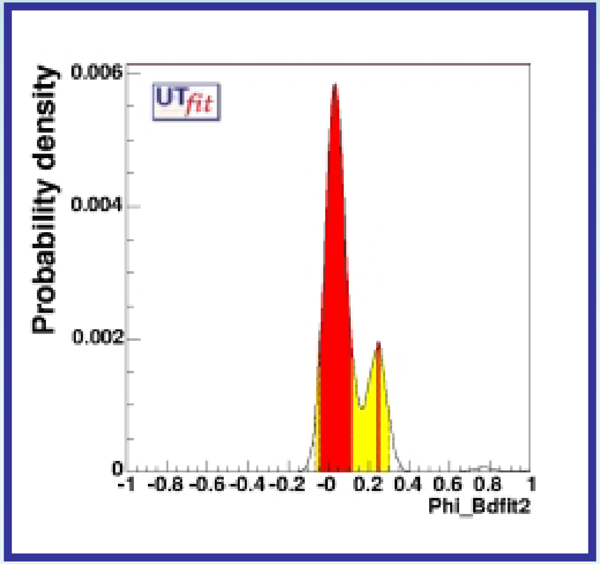
$$\Delta m_d = C_d \, (\Delta m_d)^{SM}$$

$$A(J/\psi \, K_S) \sim \sin 2(\beta + \varphi_d)$$

TWO SOLUTIONS:

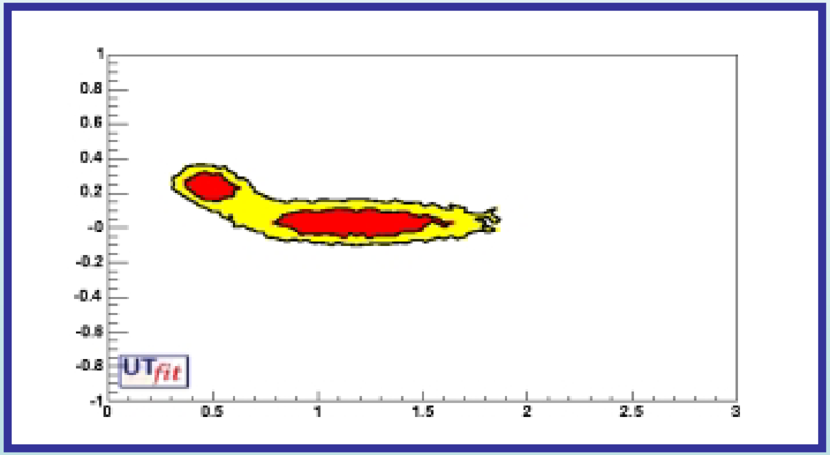
Standard Model solution:
$C_d = 1 \quad \varphi_d = 0$

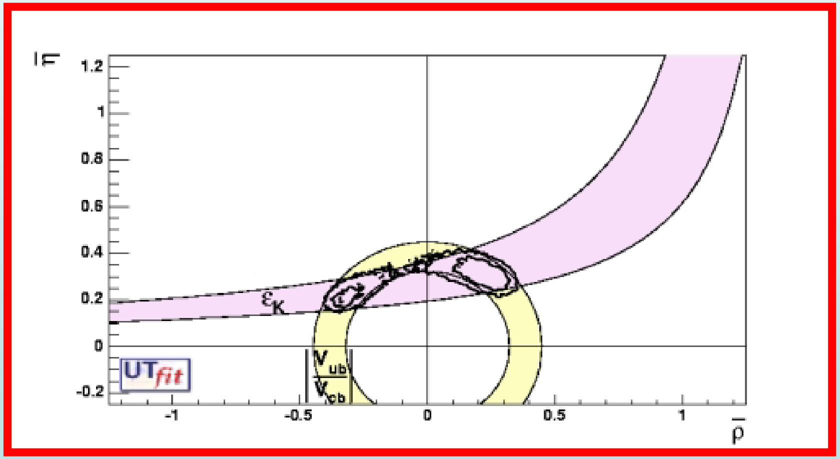




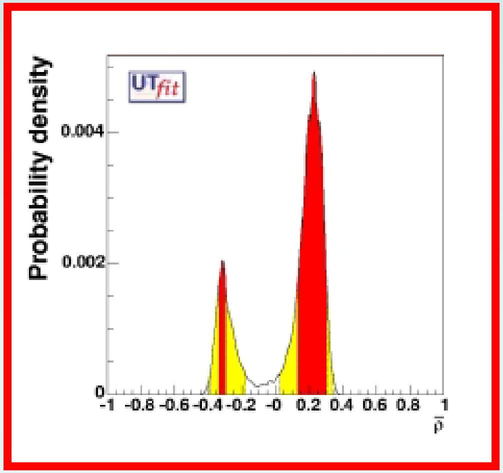
φ_d can be only determined up to a trivial twofold ambiguity:

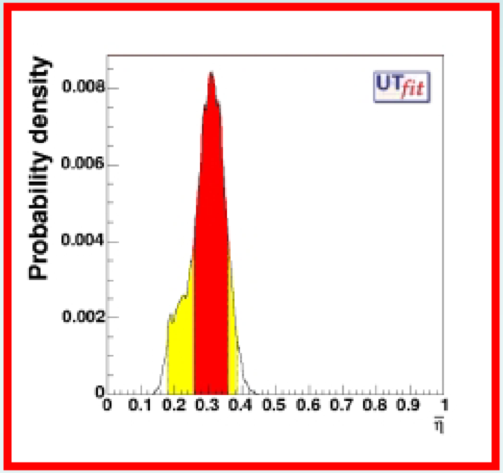
$\beta+\varphi_d \rightarrow \pi-\beta-\varphi_d$

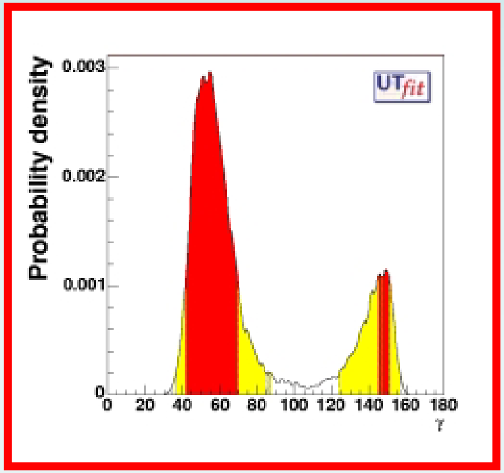




HOW CAN WE DISCRIMINATE BETWEEN THE TWO SOLUTIONS?







$\cancel{\Delta m_s}$, $\cancel{\eta\ [K_L \to \pi\nu\bar{\nu}]}$, γ [$B \to DK$], $|V_{td}|$ [$B \to \rho\gamma$], ...

γ = 81° ± 19° ± 13° (syst) ± 11° (mod)

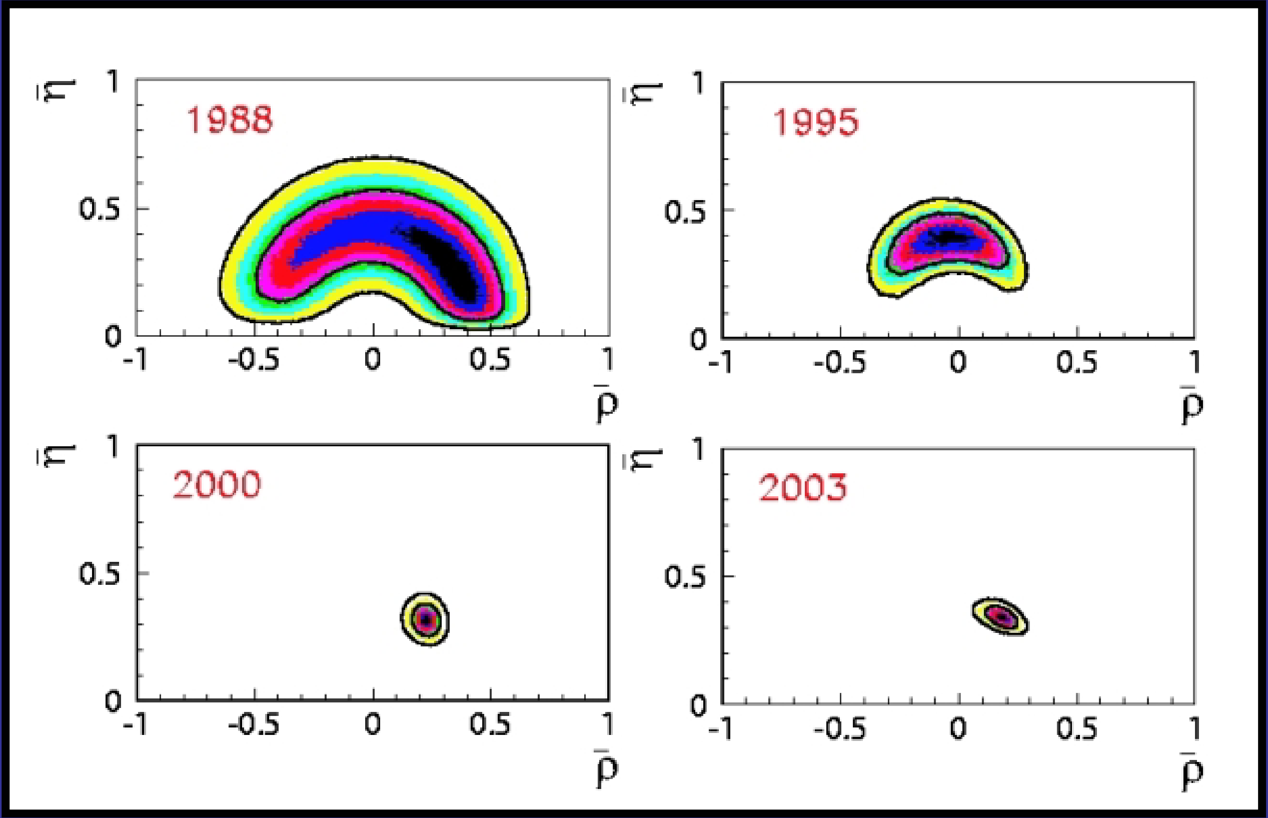
Belle **Independent of NP**

Belle preliminary + LQCD(!)

Coming back to the Standard Model:

15 YEARS OF ($\bar{\rho}$-$\bar{\eta}$) DETERMINATIONS

(The “commercial” plot)



CONCLUSIONS

- LATTICE QCD CALCULATIONS HAD A CRUCIAL IMPACT ON TESTING AND CONSTRAINING THE FLAVOR SECTOR OF THE STANDARD MODEL

- IN THE PRECISION ERA OF FLAVOR PHYSICS, LATTICE SYSTEMATIC UNCERTAINTIES MUST (AND CAN) BE FURTHER REDUCED

- IMPORTANT, BUT MORE DIFFICULT PROBLEMS (NON LEPTONIC DECAYS, RARE DECAYS, ...) ARE ALSO BEING ADDRESSED